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Research paper

Ensuring continuous feedstock supply in agricultural residue value chains: A complex interplay of five influencing factors

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ABSTRACT

While second-generation biomass resources, such as agricultural residues, are crucial for the development of the bioeconomy, value chains and markets of locally available agricultural residues remain uncommon. Current research predominantly provides useful insights into technological or techno-economic aspects of agricultural residue harvesting and processing, but, for investors in bio-refineries, one of the main challenges remains ensuring a continuous feedstock supply to the plant. In this article, we present the results of a mixed-method approach, combining insights from semi-structured interviews with simulation results of an agent-based model. This model simulates the decisions of individual economic actors in the value chain – including farmers, custom harvesters and one processor – under four coordination scenarios (direct sale, a custom harvester, mediated contract and two cooperative structures). Our results provide useful insights in the way different factors influence the ability to ensure a continuous feedstock supply. We find that besides actors' willingness, actors' coordination and supply reliability, also actors' actual participation and economic context play a crucial role. Furthermore, we are able to demonstrate the complex interplay between these factors. Our findings are relevant to guide successful future development of agricultural residue value chains for the bioeconomy.

1. Introduction

The use of agricultural residues will be crucial to realize the shift from a fuel-based economies towards a biobased economies. These second-generation biomass resources are of special interest in Europe given the ongoing food-versus-fuel debate. It was recently estimated that about 84.6 million tonnes (dry matter) agricultural residue could be sustainably harvested and used yearly in Europe [1]. However, looking to reality, their actual use for the production of materials and energy remains limited. Indeed, as long as a continuous feedstock supply cannot be guaranteed, large investments in agricultural residue processing facilities will remain unlikely. As stated by Gold and Suering (2011), biomass sourcing is “a crucial and, at the same time, vulnerable activity” [2]. In this article, we explore the different influencing factors that contribute to ensure a continuous agricultural residue supply, and how these factors influence each other. In this way, we provide insights in why local agricultural residue value chains remain uncommon, which may encourage their development in the future.

1.1. Research rationale

Current research to advance the use of agricultural residues predominantly provides useful insights into technological and techno-economic aspects of their harvest, logistics and processing. In comparison, however, relatively limited effort is spent to address the organizational challenges associated with agricultural residue value chain development. This is surprising, as the specific characteristics of local agricultural value chains demand special attention for their organization. First, due to the seasonal nature, large storage areas are needed [3–6] and equipment and workforce is concentrated in time, which can lead to inefficient use of resources [3]. Second, agricultural residues often require customized equipment for collection and handling, which further complicates the structure of the value chain [3]. Thirdly, agricultural residues generally have low bulk density and high moisture content, leading to high collection, handling and transportation costs [2–4,6]. Therefore, agricultural residue value chains are usually very local, having a typical 80–100 km (km) radius of collection [7].

Abbreviations: ABM, Agent-Based Model; CH, Custom Harvester; CSPP, Cellulosic Sugar Production Plant; DM, Dry Matter; ODD, Overview Design and Details; SOC, Soil Organic Carbon

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Besides these unique characteristics of biomass, agricultural residue value chains are also influenced by the characteristics of the economic agents involved. Indeed, these by-products are produced by a large number of farmers dispersed within the collection area of a relatively small number of processors, which increases transportation and handling costs [4–6]. Moreover, farmers are usually not only driven by rational economic goals. Other social aspects may play a role [8], including risk aversion or the tendency towards conservatism. Furthermore, farmers operate within a context and network of other economic agents, including custom harvesters. Finally, the biomass sector is characterized by a highly variable economic environment because of fluctuations in fossil fuel prices, and changing agronomic conditions and technological factors. Therefore, it is challenging, if not impossible, to create contracts that prevent opportunistic behavior [9].

As a result of these unique characteristics of both the biomass itself and the economic agents involved in biomass value chains, establishing a bioeconomy and developing new agricultural residue value chains will take more than the mere introduction of new or advanced technologies [10]. Furthermore, simply copying the organizational structure of other value chains is not feasible in most cases. Therefore, it is crucial that key stakeholders, investors, and policy makers have an adequate understanding of influencing factors that drive the challenges associated with agricultural residue value chains.

1.2. Influencing factors ensuring constant feedstock supply

According to literature, biomass value chains have two main challenges [2]. First, it is compulsory to keep the biomass input costs under control, as they often are about 50% of the total costs [2], second, a constant feedstock supply to the plant [2,11] is needed. In this article, we focus on the second aspect. Indeed, given the large volumes of biomass required in bio-refineries, they are very vulnerable to an unstable supply [12,13]. As such, biomass sourcing is one of their most important activities. According to literature, this continuous supply depends on: (1) the willingness of the actors to participate, (2) the reliability of supply and (3) the coordination of the actors involved in the value chain [2,14] (Fig. 1).

Previous research on the factors influencing a continuous feedstock supply mainly provided a qualitative perspective. The first factor, the willingness of the actors to participate, was investigated by qualitatively assessing the organizational preferences and/or perspectives of producers on biomass supply either through surveys or semi-structured interviews [15–17]. The second factor, the reliability of supply, was discussed by Ref. [18] who presented a theoretical framework for biomass production contract development in order to “improve contract negotiation processes and improve supply chain stability”. Recently, also the effectiveness of a business plan as a tool to manage several uncertainties in new and innovative firms within the context of the bioeconomy was investigated [19]. The third factor, namely the coordination of the actors involved in the value chain, was predominantly researched from the perspective of transaction cost economics [9, 20–23].

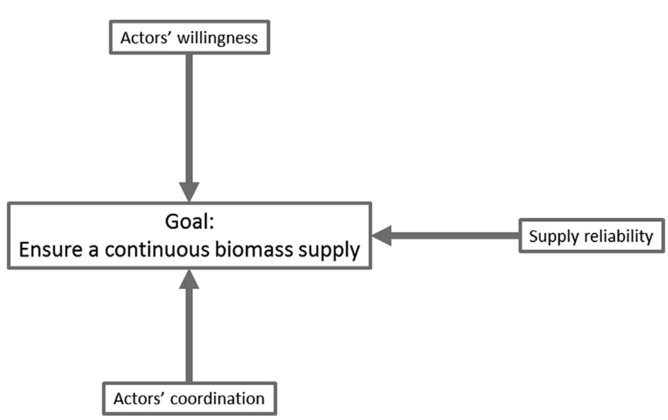

Fig. 1. Three influencing factors determining a continuous biomass supply as found in literature [14].

While these studies provide valuable insights in how these three factors influence the goal of ensuring a continuous supply, they treat each of them separately. Furthermore, they remain mainly descriptive, static and use a qualitative approach to assess the influence of different actors' coordination scenarios on the biomass value chain. In this article, we aim to integrate these three factors and to see whether additional factors also play a role. Furthermore, we investigate how they influence each other and can help in reaching the goal of ensuring a continuous agricultural residue supply, while also taking into account the innovation diffusion process and market dynamics.

1.3. Case-study: the corn stover value chain in Flanders

In order to make our work tangible, we focus on the case-study of corn stover in Flanders, the northern region of Belgium. In this region, it was estimated that yearly about 400,000 Mg (dry mass) of corn stover remains lying on the fields after harvest of the corn grain. This corn stover could potentially be used for feed [24–26], combustion [27], anaerobic digestion [28,29], or to produce bioethanol [30] or cellulosic sugars [31,32]. In order to realize this, a corn stover value chain should be established, in which sufficient farmers cultivate a corn variety of which both the grain and the stover can be harvested, and sufficient custom harvesters invest in a single-pass harvester. Despite multiple attempts to set up a corn stover value chain, this agricultural residue is neither harvested nor processed. The case of Flanders is especially interesting from an organizational perspective, as the region is characterized by a relatively large number of corn producers (about 7500), each cultivating a relatively limited number of hectares (ha) (mean = 7.63 ha) [33]. As such, the actors' willingness to participate, the supply reliability, and adequate coordination between the actors is crucial for a successful value chain. Furthermore, we could wonder whether additional influencing factors could play a role and how these factors interact with each other.

2. Method

The goal of this research is to investigate the different factors that contribute to the challenge of ensuring a stable supply of corn stover to a bio-refinery. In order to realize this, we used a mixed-method approach, integrating qualitative and quantitative research methods. According to [34], a mixed-method approach is advantageous, as it “combines the strengths of the quantitative and qualitative methods and compensates for their respective limitations”. More specifically, for this research, we integrated the results from semi-structured interviews with agent-based modelling. This modelling approach was chosen, as it allows us to explicitly take into account the individual decisions of and interactions between the different stakeholders involved in the agricultural residue value chain. Indeed, as indicated by Ref. [17], the individual decision making of farmers as feedstock providers is often disregarded in official policy documents or research. However, this decision making is crucial. Furthermore, they state that besides economic rational behavior, also non-economic considerations play a role [17]. Agent-based modelling is especially suited to take these non-economic considerations into account. In the following paragraphs, we further discuss the two methods combined.

2.1. Qualitative data to feed the agent-based model

Between March and September 2015, we conducted 14 semi-structured interviews with different experts and possible stakeholders of a corn stover value chain in Flanders (Table 1). Semi-structured interviews are a useful way to obtain a large amount of information in a

Table 1
Overview of the respondents interviewed.

Function	# Respondents
Farmer	3
Representative farmers' organization	1
Custom harvester	4
Representative from industry	3
Policy maker	1
Researcher	2
Total	**14**

limited amount of time [35].

All interviews were recorded, fully transcribed and thematically analysed [36] using NVIVO 11. We used the narrative data from these semi-structured interviews to construct the agent-based model (ABM). This way of using qualitative data from semi-structured interviews was also suggested by Boero and Squazzoni (2005) [37] and has been applied by multiple researchers (e.g. Refs. [38–42]). The insights from the semi-structured interviews were complemented with a literature study on the techno-economic aspects of corn stover harvest, logistics and processing (e.g. Refs. [30,43–49]), and on the organizational aspects of biomass value chains (e.g. Refs. [16,18,19,50]). From these analyses, we were able to identify the main economic actors influencing the value chain, and their main behavioral rules, which was needed to develop the ABM. After a preliminary version of the model was developed, a workshop was organized for different experts of corn stover harvest, logistics and processing. In this workshop, with 9 participants, the model and the preliminary results were presented and feedback from the participants was taken into account to build the final model.

2.2. Agent-based modelling

The goal of ABMs is to help researchers to understand the mechanisms operating at the micro level of a system, in our case the value chain, that lead to the specific features observed at the macro-level, being the supply certainty. As such, we developed an ABM to help us understand the factors at the micro level (e.g. actors' willingness to participate, reliability of supply, and actors' coordination) that lead to the challenge observed at the macro level; ensuring a continuous feedstock supply. More specifically, the ABM presented in this article simulated the behavior of, and interactions between, the main economic actors influencing the value chain, identified from the semi-structured interviews.

The advantage of agent-based modelling is that it allows researchers to take into account the heterogeneous, bounded rational, sociological and strategic decision-making aspects of the actors. Therefore, some assumptions from other modelling approaches, such as economic rational behavior or equilibria can be relaxed [51,52]. Furthermore, agent-based modelling allows the modeler to represent economic systems in a natural way [52,53].

Multiple studies have used ABMs to gain insight in market mechanisms of biomass value chains. For example, an ABM was used to study the development of switch grass biofuel and bioelectrivity market at the local level [54]. Also the adaptation of Miscanthus production by farmers in Illinois and the impact on biorefinery capacity and contractual agreements was explored using an ABM, [55]. Agent-based modelling was also used to estimate corn stover removal rates and the transboundary effect along the bioenergy value chain in Iowa [46]. Finally, an ABM was developed to assess the impact of market context on the supply of local biomass for anaerobic digestion plants [56]. More detailed information on ABMs can be found in Refs. [52,53,57]. We

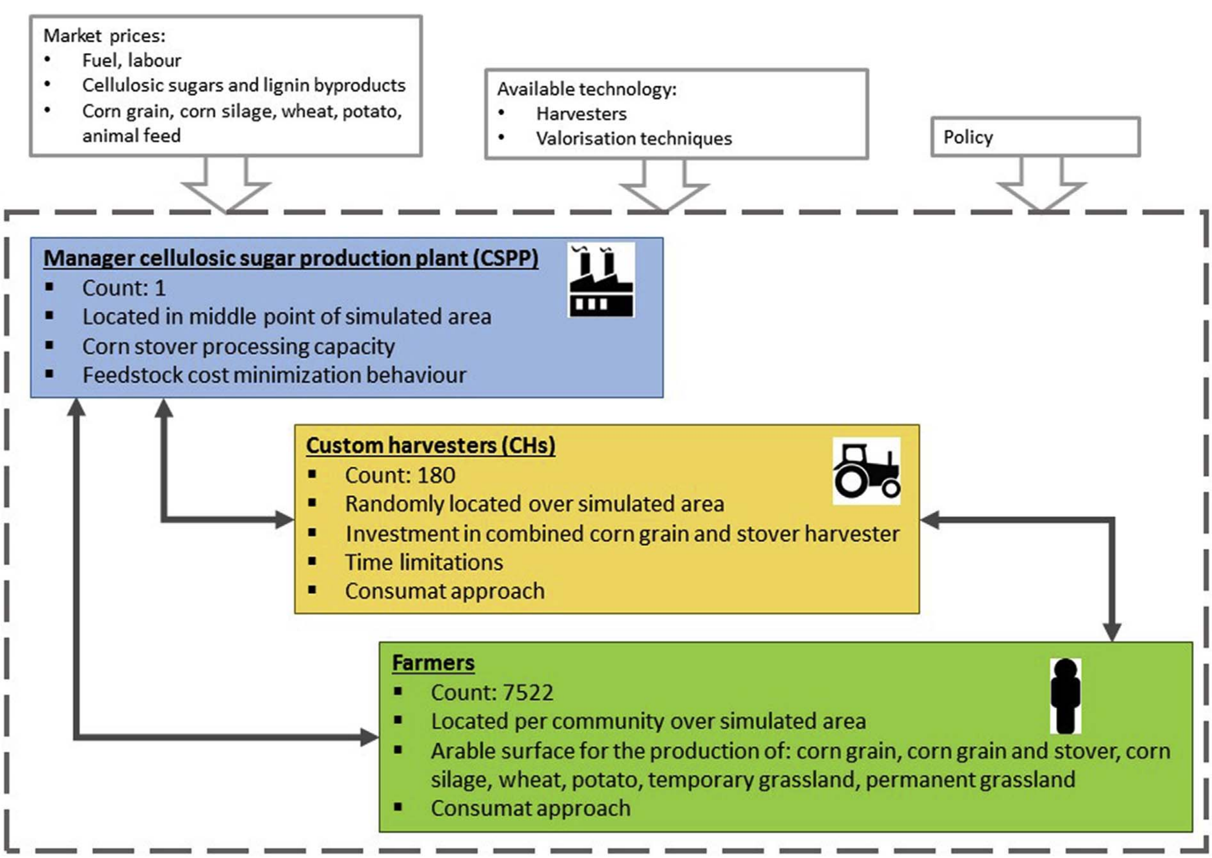

Fig. 2. Schematic overview of the ABM. Three main agents were identified (a cellulosic sugar production plant, custom harvesters and farmers) and included in the model. Their main characteristics are presented in the colored boxes. The dashed rectangle represents the model boundary. Parameters mentioned outside the model boundary are exogenous to the model and derived from literature.

developed our model in R [58].

3. General model description

This section briefly describes the main structure of the ABM we developed. As we do not have the space, nor the intention to explain the full details of the model in this article, readers, interested in specific model details, can have access to a complete model description following the Overview, Design and Details (ODD) protocol [59,60] in the supplemental web enabled material.

3.1. Agents

The qualitative research allowed us to identify the main actors involved in a possible corn stover value in Flanders. As can be seen in Fig. 2, three such actors were identified; farmers, custom harvesters (CHs), and processors.

We decided to model only one processor type: a cellulosic sugar production plant (CSPP), converting the corn stover into cellulosic sugars and lignin by-product. This processing option was chosen, because during the interviews and the workshop, the respondents indicated that a high value end product, like cellulosic sugars, would be needed for a successful value chain, while it was indicated that the price of other products, including bio-ethanol, would likely be too low to cover the production, collection and processing costs. As such, we included a CSPP in the model. Specific techno-economic data on such a plant could be found in literature [31,32]. We assumed that the CSPP is located in the center of the simulated area and has a maximum capacity of 250,000 Mg (dry basis). We assumed that the CSPP aims to purchase feedstock at the lowest price possible, and will not be willing to pay more than a predefined ceiled sum of 117.27 € Mg^{-1} [31].

Moreover, from the qualitative research, we identified custom harvesters (CHs) as main actors in a potential corn stover value chain in Flanders, as they would be responsible not only for corn grain harvest, but also corn stover harvest. Therefore, in our model, we included 180 CHs. In the model they are randomly located over the simulated area. During the semi-structured interviews, CHs underlined the limited harvest time for corn grain, which we explicitly included in the model as a maximum harvest capacity of 400 ha $year^{-1}$ for corn grain, and 300 ha $year^{-1}$ for corn grain and corn stover, assuming a single-pass harvesting system [61].

Finally, farmers, the corn stover producers, were identified as main economic actors in the potential value chain. Farm data were retrieved from the Belgian Farm Structure Survey of 2010. As such, we were able to identify 7522 farmers that grew corn grain in 2010. From this survey, we could identify the name of their municipality, as well as the surface of their farmland and for which crops they used this farmland. As the survey did not contain data on their exact location, we assumed all farmers to be located in the center of their respective municipality. In the model, we assumed that farmers can choose to cultivate following crops: corn grain; corn silage; potato; wheat; temporary and permanent grassland. We selected these crops, as 95% of the farmland cultivated by corn farmers in Flanders is covered by them [33]. Farmers can also choose to grow a corn variety of which both the grain and the stover can be harvested. However, these varieties generally have a lower yield. In the model, farmers are considered to be price-takers: they have to sell their crops at market price, and have no influence on these prices themselves. The model input data for these prices were the yearly average crop prices from 2003 until 2014, following [62,63] (Fig. 3). We observe significant price fluctuations. However, as they are derived from statistical data, they can be considered representative.

3.2. Behavioral rules: consumat approach

The semi-structured interviews with farmers and CHs revealed that decisions to adapt a new agricultural practice, such as corn stover harvest, or investment decisions (e.g. decisions to invest in a single-pass harvester) are not only based on economic criteria, like profitability, but also depend on other factors, including risk aversion, or conservatism to certain behavior. Therefore, we assumed that both CHs and farmers follow the consumat approach to decide on investment decisions, crop selection and allocation respectively. The consumat approach, a meta-model of human behavior, integrates insights from expert-theories on human behavior [64]. The meta-model is based on two main principles. Firstly, people follow a satisfying behavior instead of always making optimal decisions [65]. This can be attributed to limited time and cognitive resources [64], meaning that people are not able to constantly evaluate all possible options and outcomes to determine the optimal decision [64]. Consequently, people repeat certain behaviors as long as they are satisfied and, and create habits. Secondly, people observe other people's behavior and use this information to acquire knowledge on new attractive behaviors [18,64]. Hence, people who are uncertain about their decisions mimic the behavior of others. This behavior is even more prominent when decisions are complex and have serious repercussions, such as making investments to join an innovative value chain [18].

The consumat approach is based on two variables: economic satisfaction and uncertainty. First, in our model, economic satisfaction can be regarded as a proxy for the answer to the question "Am I happy with my revenue, given my current assets (e.g. arable land or machinery). In our model, the economic satisfaction is calculated as the ratio of the agents' actual gross margin over his potential maximum gross margin. Second, the uncertainty value is a proxy for: "How certain am I that may cropping plan or machinery investment decisions were good decisions, given the economic performance of the other farmers or custom harvesters?". In our model, the uncertainty value is calculated as the ratio of the agents' actual gross margin over his expected gross margin. In the supplemental web enabled material, we detail how these two variables are calculated, for both the farmers and the CHs.

The combination of the economic satisfaction and uncertainty leads to four behavioral rules (Fig. 4).

(1) **Repetition:** applied by agents that are satisfied with their economic performance and certain about the decisions they make. They are not inclined to change their behavior. Farmers keep their current cropping plan and CHs will not consider investing in a new single-pass harvester.
(2) **Imitation:** applied by agents that are satisfied with their economic performance, but uncertain about their decisions. Farmers will imitate the cropping plan of the farmer with the highest gross margin in their close network, which are the farmers within a 10 km radius. CHs will consider purchasing a single-pass harvester if they have a stover harvesting contract that year and if more than half of the CHs in their close network already did. The close network of a CH is determined by a random Erdös-Renyi network [67], in which each CH has a probability of 0.3 to be connected to another CH. For each connection, we randomly sampled a weight between 0 and 1. Links with a weight equal or larger than 0.5 represents the close network of the CH.
(3) **Social comparison:** applied by agents that are unsatisfied from an economic perspective and uncertain about their decisions. Farmers will copy the cropping plan of the farmer with the highest gross margin in their broad network, which are all farmers within the same agro-ecological region. This behavior occurs during farmers' networking days focusing on economic performance comparisons in order to identify improvements. CHs will consider purchasing a single-pass harvester if they have a stover harvesting contract that year and if more than half of the CHs in their broad network already did. The broad network of a CH is determined by the same Erdös-Renyi network mentioned above. However, in this case all links represent the broad network of the CH.
(4) **Deliberation:** applied by agents with a low economic satisfaction

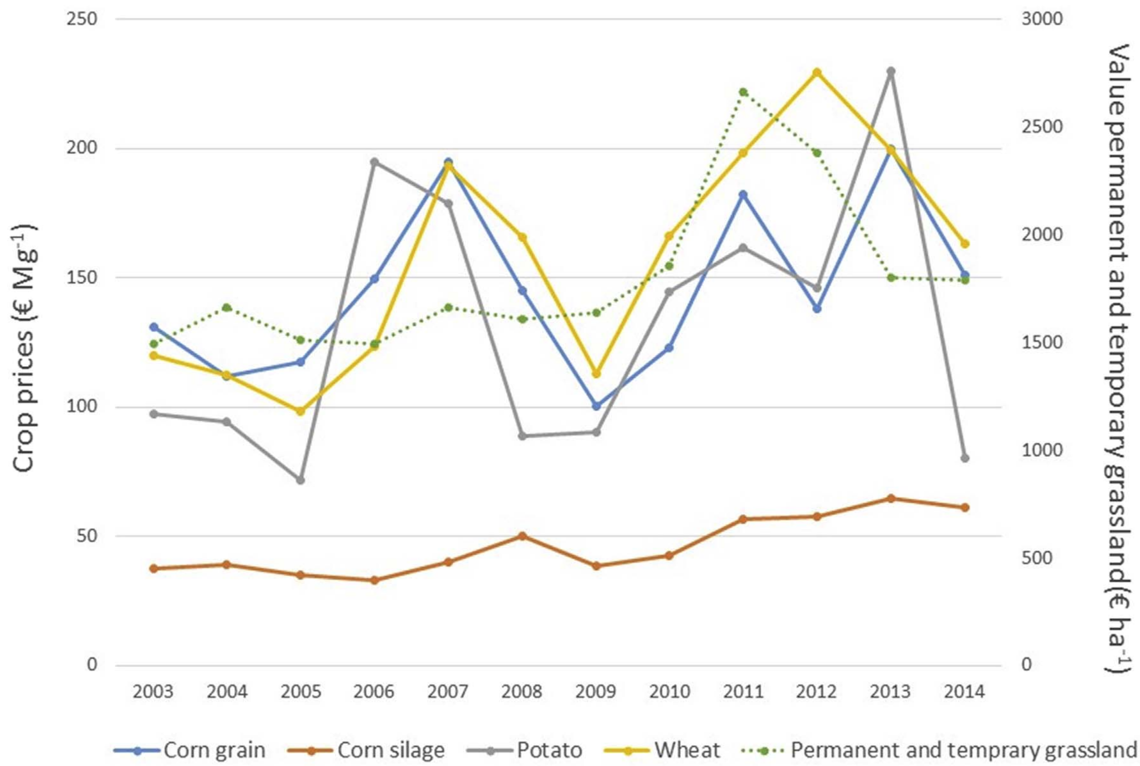

Fig. 3. Prices of corn grain, corn silage, potato, wheat, expressed in € Mg^{-1}. The values of permanent and temporary grassland (dashed green line) are expressed in € ha^{-1}. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

who are certain about their decisions. Deliberating farmers will optimize their gross margin by optimizing their cropping plan given current crop prices and crop rotation restrictions. Deliberating CHs will consider purchasing a single-pass harvester if the net present value of their investment is positive, but they will only invest if they have a stover harvesting contract that year. In the supplemented web enabled material, we detail how the net present value is calculated.

The behavioral rule that each farmer or CH will follow is yearly determined as follows. The agent calculates his economic satisfaction and uncertainty value and compares it with the individually determined threshold parameters: the aspiration level and uncertainty tolerance, respectively. When the economic satisfaction is higher than the aspiration level, he will either follow a repetition or imitation behavior. Vice versa, when the economic satisfaction is lower than the aspiration level, he will either follow a deliberation or social comparison behavior. Similar for the uncertainty value, when the uncertainty value is higher than the uncertainty tolerance, he will follow an imitation or social comparison behavior. Vice-versa, when the uncertainty value is lower than the uncertainty tolerance, he will follow an repetition or deliberation behavior. The aspiration level and uncertainty tolerance parameters are individually and randomly sampled for each farmer and CH upon model initialization from a normal distribution with a mean value of 0.5 and standard deviation of 0.17 [66].

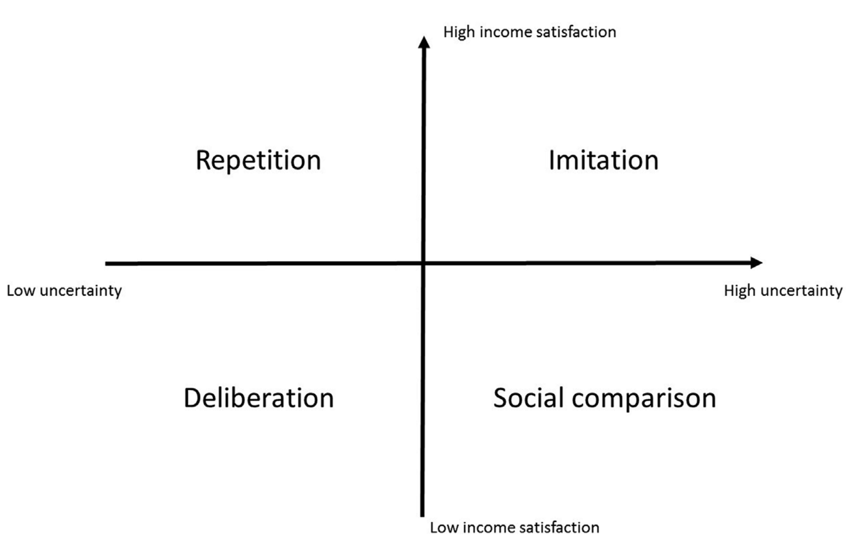

Fig. 4. Two variables included in the consumat approach, leading to four behavioral rules (based on [64,66]).

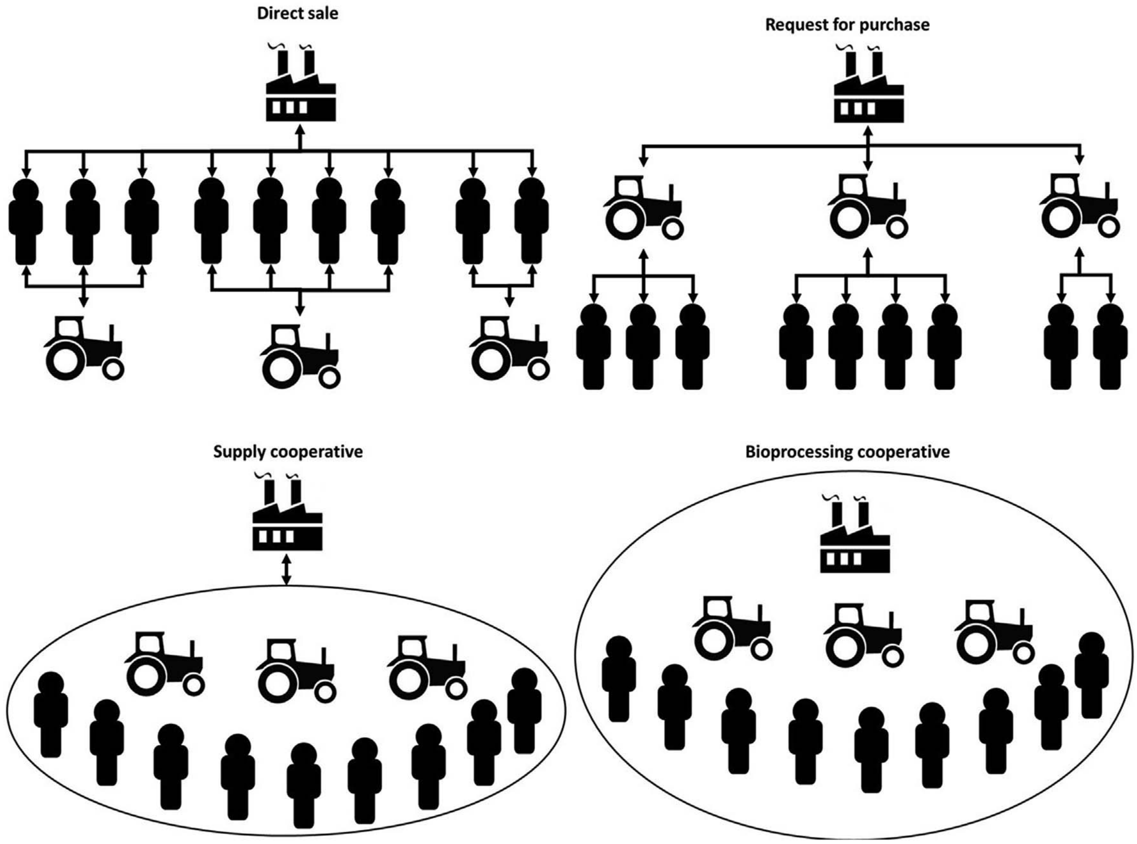

Fig. 5. Schematic overview of the actor coordination scenarios. The CSPP is represented as a factory, the CHs as tractors and the farmers as persons. Two-sided arrows represent negotiation processes. Circled agents are part of a cooperative.

3.3. Scenario analysis: comparison of four actor coordination scenarios

In order to explore how the factors identified in literature contribute to ensuring a continuous agricultural residue supply, to investigate whether there are additional factors, and how they interact, we applied our ABM to four scenarios, each representing a different level of actor coordination (Fig. 5). While these scenarios are based on [31], they are also discussed by other researchers (e.g. Refs. [20,23]).

The first scenario is called "Direct sale". In this scenario, there is hardly any coordination of the economic actors. Farmers interested in selling stover negotiate individually with the CSPP about the corn stover price. They are responsible for the harvest and transportation of the stover to the processing plant and also bear the costs of these activities. In order to harvest their corn stover, farmers need to find a CH that is willing to invest or has already invested in a single-pass harvester. In the second scenario, called "request-for-purchase", the economic actors are slightly more coordinated, as the CHs act as intermediaries between the farmers and the CSPP. Participating CHs contract a certain volume of stover to be delivered to the CSPP at a certain price. In this case, the CHs are responsible for the harvest and transportation costs and need to look for farmers that are willing to sell their stover. In the third scenario, called "supply cooperative", farmers and CHs are well coordinated and united in a cooperative organization. The supply cooperative aims to efficiently organize the corn stover harvest and logistics and negotiates as a single entity about the corn stover supply conditions with the CSPP. Finally, in the fourth scenario, called "bioprocessing cooperative", all economic actors are highly coordinated in a cooperative that involves farmers, CHs, and the CSPP. The goal of the bioprocessing cooperative is to efficiently organize the total corn stover value chain in such a way that each member contributes to, but also shares in the profit made by the CSPP. Detailed information on how these four scenarios are implemented in the ABM can be found in the supplemented web enabled material.

4. Results

The simulation results below present the averages of 100 runs for each actor coordination scenario (direct sale, request-for-purchase, supply cooperative, and bioprocessing cooperative). This number of runs is necessary to capture stochastic effects and to provide general estimations. As the results are influenced by the historic crop prices (2003–2014) included in the model, the results are framed in this period. More concretely, in the section below we evaluate the effect of the coordination of actors in different coordination scenarios on the willingness of the main actors to participate (section 4.1 and 4.2) and on the supply reliability in Flanders (section 4.3), if a CSPP would have been operational from 2003 onwards. Due to stochasticity, the model is not suited to forecast exact market behavior of individual agents. The results should, therefore, be interpreted in light of general market dynamics. For all statistical significance tests, we used a Mann-Whitney *U* test.

4.1. Farmers: willingness and actual participation

Fig. 6 shows, for each scenario, the predicted farmers' willingness to participate in the corn stover value chain, expressed as the share of farmers' willing to participate(left), and farmers' participation expressed as the share that would have actually participated (right), between 2003 and 2014.

Overall, farmers' willingness follows the same trend for the four actor coordination scenarios. In each scenario, it would have started at a relatively high level (48%), to drop significantly in 2004 to even 0% for the direct sale and request-for-purchase scenarios and to 4% for the cooperative scenarios, and to eventually increase again in 2007 (to

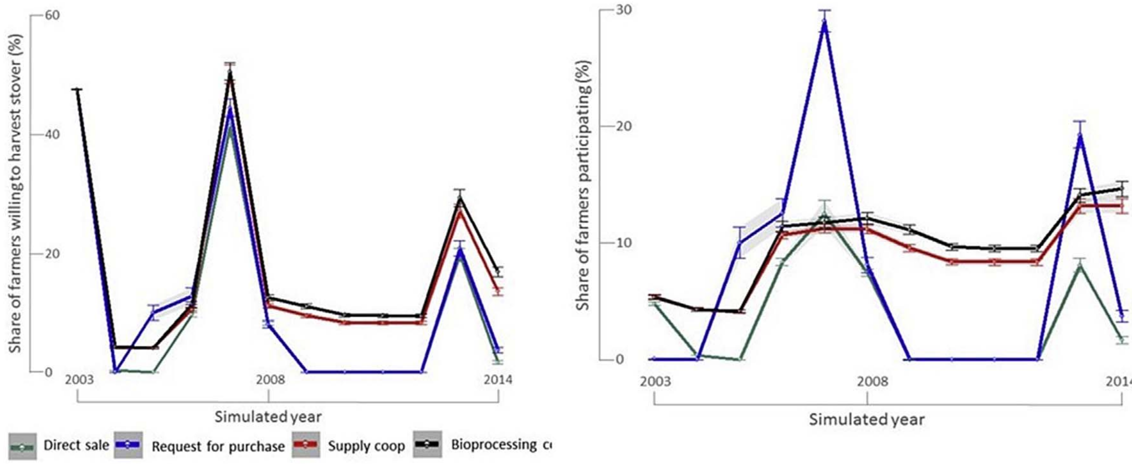

Fig. 6. Left: Farmers' wiliness to participate in the corn stover value chain (%) and right: Farmers' participation in the corn stover value chain (%) for the four scenarios. The error bars and the grey ribbon represent the 95% confidence interval.

41%, 45%, 50% and 51% for the direct sale, request-for-purchase, supply cooperative and bioprocessing cooperative scenarios respectively). For the direct-sale and request-for-purchase scenarios, the predicted farmers' willingness would have dropped again to almost 0% from 2009 to 2012. For the cooperative scenarios, this level would have stayed between 8% and 10%. There would be no significant difference in farmers' willingness between the direct sale and request-for-purchase scenarios between 2009 and 2013. For the same period, farmers' willingness would have been slightly, but significantly ($p < .05$), higher in the bioprocessing cooperative scenario than in the supply cooperative scenario. These fluctuations can be explained by looking at the prices of the other crops grown by the farmers (Fig. 3).

These fluctuations can be explained by looking at the prices of the other crops grown by the farmers (Fig. 3). These prices determine the actual gross margin and the expected revenue of the farmers. Our results show that in general, farmers follow a deliberation behavior and to a lesser extent a social comparison behavior. Fewer farmers follow a repetition behavior, and almost no farmers follow an imitation behavior. In 2009, the prices of wheat, potato and grain were relatively low. Having a lower revenue than the expected revenue, farmers become uncertain about their decisions and more farmers switch to a social comparison behavior, at the cost of farmers with repetition behavior. As such, large shifts in cropping plan occur. Over the following years, prices of wheat and permanent grassland are relatively high. As a result, more farmers grow these crops instead of corn. Consequently, fewer farmers would have shown interest in participating in the corn stover value chain.

The farmers' participation shows a rather unstable pattern in both the direct sale and request-for-purchase scenarios and follows largely the same trend as farmers' willingness. For the request-for-purchase scenario, this pattern is most pronounced. The cooperative scenarios show a more gradual increase in farmers' participation. Starting from 2008, farmers' participation in the bioprocessing cooperative would have been slightly, but significantly ($p < .05$), higher than in the supply cooperative scenario.

Remarkably, for all scenarios, the predicted farmers' willingness would be most often larger than farmers' participation. This is explained by the behavior of the CHs, discussed in the next section.

4.2. Custom harvesters' participation

The left pane of Fig. 7 shows the predicted custom harvesters' participation, expressed as the share of CHs owning a single-pass harvester. Custom harvesters' participation remains limited to 25% for the direct sale and supply cooperative scenarios and 27% for the bioprocessing cooperative scenario. In the request-for-purchase scenario, up to 34% of the CHs would have bought a single-pass harvester by 2014. The comparison of Fig. 7 with Fig. 6 indicates that the number of single-pass harvesters, each able to harvest 300 ha per year, as explained in section 3, limits farmers' participation. For example, in 2007 of the bioprocessing scenario, 51% of the farmers would have been willing to participate, which would result in a corn stover harvesting area of about 38,516 ha. The graph shows that only 22% of the CHs would own a single-pass harvester in 2007, which makes a total harvest area of only 11,880 ha. Indeed, in this year and scenario, 12% of the farmers actually participate in the corn stover value chain, which corresponds to an area of 9063 ha of corn planted for harvest of the grain and stover. The difference between the maximal possible surface and the actual surface harvested is explained by limitations in transportation distance, and differences in yield between different agro-ecological zones, as well as differences in coordination of the actors, which is further discussed in section 5. This result demonstrates the key position of the CHs in the corn stover value chain: a deficit in single-pass harvesters limits farmers' participation in the value chain. Indeed, in the request-for-purchase scenario, the CH has a central position in the value chain, and a coordinating role, leading to an increased number of CHs owning a single-pass harvester.

Due to their central position, however, CHs are also very vulnerable to changes in the market. Because the farmers' willingness and participation is dynamic, CHs face a large risk not to be able to fully use their equipment at certain points in time. This overcapacity is presented in the right pane of Fig. 7, showing the predicted number of single-pass harvesters in surplus given the surface of corn planted for the harvest of both the grain and the stover. With regard to the direct sale scenario, and even more for the request-for-purchase scenario, we observe a large surplus of up to 59 single-pass harvesters between 2008 and 2014. In these years, many CHs would not have been able to use their equipment to the full extent or even not at all and their investment would not have been profitable. In the supply cooperative and bioprocessing cooperative scenarios the surplus remains limited to a maximum of 18 single-pass harvesters. If farmers' participation rate is more stable, as in the cooperative scenarios, the CHs would have been more likely to use their equipment every year, at least to harvest some hectares.

4.3. Supply reliability

Fig. 8 shows the predicted corn stover volume purchased by the CSPP as a percentage of the maximum processing capacity of the plant (250,000 Mg dry basis). In fact, this graph illustrates the accumulation of the decisions of both the farmers and the CHs whether or not to

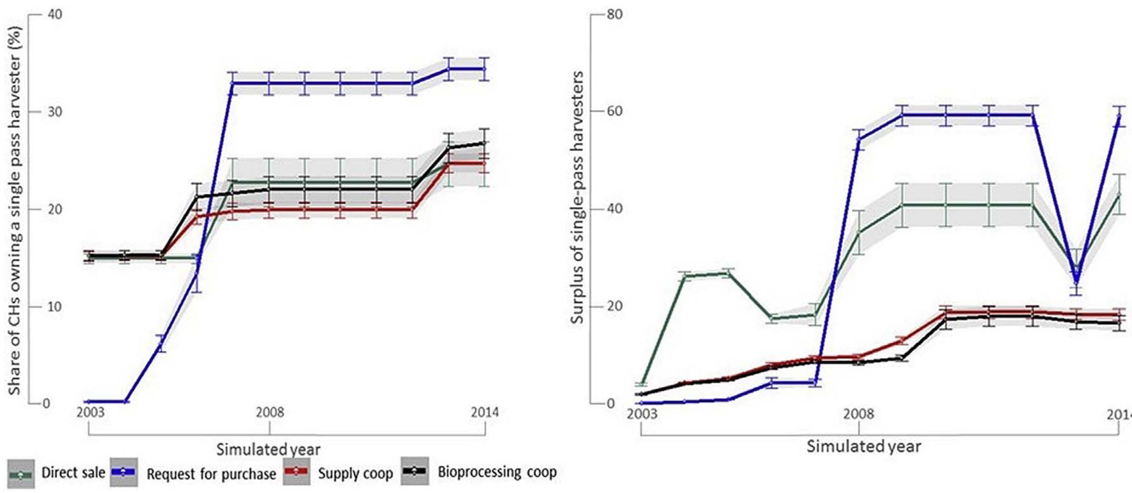

Fig. 7. Left: Custom harvesters' participation, expressed as the CHs owning a single-pass harvester for the four scenarios (%). Right: Number of single-pass harvesters for the four scenarios. The error bars and the grey ribbon represent the 95% confidence interval.

participate in the corn stover value chain, and how supply reliability is influenced by actors' willingness to participate and coordination of these actors. The direct sale scenario would have shown a rather fluctuating trend, in which supplies would have raised up to about 18% and 12% in 2007 and 2013 respectively, but also would have dropped between 2009 and 2012. The corn stover supply in the request-for-purchase scenario would have shown a similar trend, only the fluctuations would be more pronounced with supply peaks of up to 43% and 29% in 2007 and 2013 respectively. These patterns are in accordance to the predicted farmers' participation (Fig. 6). The supply cooperative and bioprocessing cooperative scenarios would have shown significantly smaller fluctuations in the corn stover supply. In the supply cooperative scenario, the purchased volumes would have fluctuated between 12% and 19%. For the bioprocessing cooperative scenario, these volumes would be higher and would fluctuate between 17% and 25%. Finally, for all scenarios, we observe that if a CSPP would have been operational in 2003, the plant could never have acquired the necessary corn stover volumes to operate at full capacity. Indeed, the volumes purchased would have fluctuated around 20%, which means that the CSPP could only have acquired a reliable supply of about 50,000 Mg dry basis.

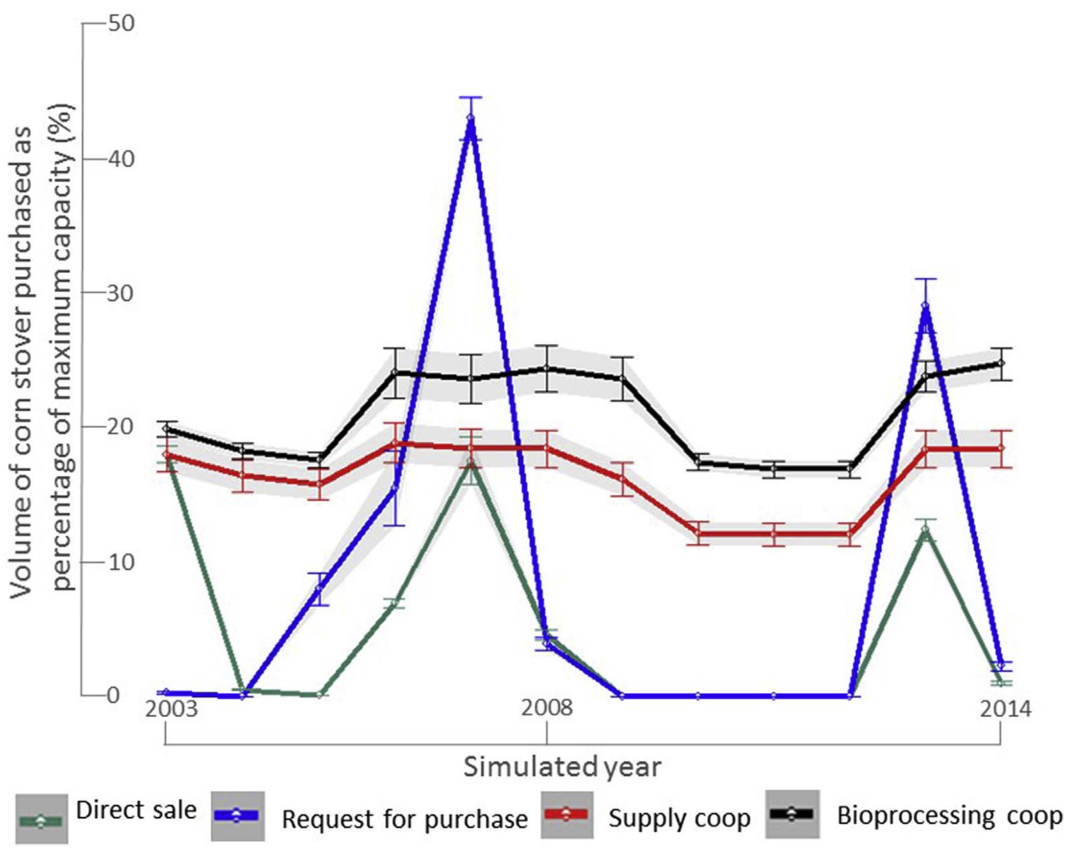

Fig. 8. Volume of corn stover purchased by the CSPP as a percentage of the maximum processing capacity for the four scenarios. The error bars and the grey ribbon represent the 95% confidence interval.

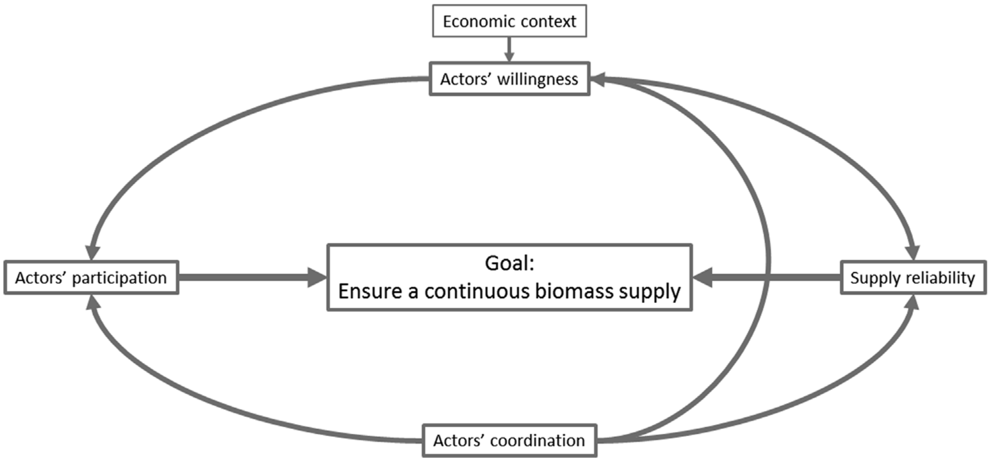

Fig. 9. Influencing factors and their interactions determining a continuous supply of agricultural residues.

5. Discussion

The model results allow us to gain insight into how the three aspects (actors' willingness, actors' coordination and supply reliability) help in reaching the goal of ensuring a continuous agricultural residue supply. Furthermore, they reveal the complex interplay between these factors. Our results provide both insights for the specific case of a corn stover value chain in Flanders, or similar regions, but also more general insights valuable for economic actors interested in the much needed development of agricultural residue value chains. Therefore, below, we present a more elaborate discussion of the model results in a more general context (section 5.1), and shortly discuss the implications of our results for Flanders or a similar region (section 5.2). Finally, we also discuss the model assumptions (section 5.4) and possible venues for further research (section 5.4).

5.1. General research implications

Our results allowed us to refine Fig. 1, resulting in Fig. 9. Besides the three influencing factors identified from literature, in this figure, we added two additional factors, namely economic context and actors' participation. Furthermore, we schematically represent their complex interplay. This will be further discussed in the following sections.

5.1.1. Actors' willingness and participation

As mentioned before, and as shown in Fig. 1, the economic actors' willingness to participate in agricultural residue value chains was identified as one of the main aspects of establishing a continuous biomass supply to large-scale processing plants [14]. Hence, several authors have done research on the actors' willingness to participate in new biomass value chains, and more particularly on the willingness of the producers to supply biomass to a processing plant (e.g. Refs. [16,68,69]). In general, these studies take a static approach and therefore provide a snapshot of the producers' willingness at a certain point in time.

While existing willingness research was crucial to get a first insight in assessing the potential biomass supply to a large-scale processing plant, the case-study shows that these studies are only a first step, and a one-on-one relationship is unlikely for two reasons.

First, we demonstrated that producers' willingness cannot be regarded as a static concept, but can be highly dynamic and dependent on other economic factors, including prices of other crops. Indeed, literature has shown that an uncertain business climate could change the outcome of the survey results [16]. As such, potential investors in agricultural residue value chains should be aware of these dynamics in producers' willingness. In future research, it might therefore be useful to take a more dynamic modelling approach, or to use panel survey data in order to show how changing economic conditions interplay with farmers' willingness.

Second, we demonstrated that producers' willingness is not sufficient as explaining factor to understand how a continuous biomass supply can be ensured. Indeed, our results showed that in fact it is farmers' actual participation that influences the agricultural residue supply. Therefore, investors in new agricultural biomass value chains should not be biased by data on producers willingness only, but should instead critically reflect whether the necessary preconditions were created for these interested producers to be able to actually participate. As such, it is important to reflect on the willingness of all possible stakeholders in the value chain.

5.1.2. Influence of actors' coordination on actors' willingness, actors' participation and supply reliability

As discussed in the previous section, actors' willingness is not sufficient to assess the potential biomass supply to a processor, but actual participation is of main importance. In the case-study, actors' participation is not only influenced by their willingness, but also by the actors' coordination. A clear example of this can be found when we compare the results of the direct sale and the request-for-purchase scenario. While we could not find any significant difference between the farmers' willingness for these scenarios, we observe that the farmers' participation largely deviates, with large peaks in the request-for-purchase scenario and more moderate peaks in the direct sale scenario. We also observe a significant difference in the custom harvesters' participation for these two scenarios. As such, we find that the actors' coordination with the custom harvester in a central position, allows for a better coordination and alignment of the different actors in the value chain. However, the largely fluctuating farmers' willingness resulting from changes in economic context, leads to a higher chance of a potential mismatch between farmers' willingness and CHs who have invested in a single-pass harvester. Therefore, the case-study shows the CH's key position, but at the same time very vulnerable position, in the corn stover value chain. In the literature, their role is often neglected. When CHs are an intrinsic part of the agricultural system, one should recognize their central position and make significant effort to involve them from the start when developing new agricultural residue value chains [70]. In other regions, where farmers are not used to working with CHs, investors should be aware that the CHs' role might expand over time, as the equipment becomes more and more specialized and capital intensive [71].

Furthermore, we find that actors' coordination also influences supply reliability, and through this aspect, indirectly influences the stability of the biomass supply, rather than having a direct influence.

The main characteristic in the direct sale and request-for-purchase scenario is that the farmers can easily enter and exit the market whenever they want [31], which is also reflected in the case-study, showing a large fluctuation in the farmers' participation. This can be perceived as an advantage for the farmers, but when agents need to make large investments, such as the CHs and the CSPP, the easy entry and exit can also be perceived as a major threat for these agents, as it exposes them to an unstable biomass supply [70,72]. Famers' engagement in the market may suddenly drop, leaving the CHs with an expensive single-pass harvester that cannot be used, and the CSPP with an unstable corn stover supply. Therefore, under these coordination scenarios, investments are too risky. Another disadvantage of a direct sale coordination scenario is that the CSPP needs to manage separate contracts with hundreds of farmers. Managing such a large number of contracts is often found undesirable by processors [31]. As such, we can conclude that a direct sale and request-for-purchase coordination scenario are not the most favorable ways to organize the value chain.

The two cooperative actor coordination scenarios have the advantage of a more equal distribution of both profit and risks between the actors in the value chain [31]. In our results, this is reflected by the higher farmers' willingness under these actor coordination scenarios. Additionally, these coordination types give their members a sense of ownership and profit motivation [73]. However, we were not able to take these two features explicitly into account in the model. Overall, we found that the cooperative actor coordination scenarios give a more stable, and reliable farmers' willingness and participation. This is beneficial, both for the custom harvesters, as a mismatch between the farmers' participation and the number of machines is largely avoided, and for the processor, as the agricultural residue supply is found to be far more stable.

5.2. Research implications for Flanders or similar regions

With regard to the case-study, the development of a corn stover value chain in Flanders, we can also learn some interesting lessons. Firstly, irrespectively of the simulated actor coordination scenario, we found that a large-scale breakthrough of the simulated CSPP only based on corn stover would have been unlikely between 2003 and 2014. Although the corn stover supply in the request-for-purchase scenario reached almost half of the operation capacity at certain points in time, a corn stover supply at this level could not be maintained over a longer period. For the two cooperative coordination scenarios, the CSPP operation capacity fluctuates around 20% of its maximum. In a region such as Flanders, with relatively small scale farmers and fields, several options exists: to use the corn stover in smaller scale processes, producing high value products; to ensure a continuous supply by complementing the corn stover supply with for example wheat straw, wood chips or miscanthus.

5.3. Study limitations

In order to improve confidence in model-based conclusions, it is necessary to assess how model assumptions and parameters alter the results and policy decisions [74]. On one hand, we might underestimate the development for several reasons. We assumed that stover can only be harvested from maize specifically sown for this purpose. In practice, farmers could also decide to harvest the stover of silage maize when the price incentive is large enough. Also the land availability for each farmer can increase or decrease over time. We excluded certain economic parameters such as oil prices. A rise in oil prices may, for example, induce higher prices for bio-based products and therefore foster the implementation of the bio-economy. Additionally, we only considered corn stover produced within Flanders and did not consider any import from other regions or countries. This assumption can be justified by the fact that stakeholders indicated that due to the low corn stover density, transportation of this biomass over longer distances than 100 km is not likely to be economically viable. On the other hand, we might overestimate the stover supply since we did not take into account inter-year variability of corn stover yields, discussed by Ref. [74], nor the risk of not being able to harvest the corn stover due to extreme wet weather conditions. Following [66], we assumed the uncertainty values and aspiration levels to have an average value of 0.5 and a standard deviation of 0.17 for the farmers and the CHs. Nonetheless, a sensitivity analysis, of which the results are discussed in the supplemental web enabled material, indicated that our main conclusions are still valid in case of certain parameter changes, including the uncertainty values and the aspiration levels. Finally, we did not take into account all possible market mechanisms and actor coordination scenarios, e.g. long-term contracts. Long-term contracts are however not likely to be the best option in case of cellulosic sugar production, as this would significantly increase the CSPP's capital requirements compared to cooperative models [73], and because it may be difficult to convince farmers to sign such contracts. The selection of actor coordination scenarios is based on [31] and the model detail, was guided by the combination of model complexity to approximate reality, feasibility of parameter estimation and output interpretability. In addition, the model was constructed, not with the aim of producing individual-level results, but rather to gain insights in the mechanisms that influence and contribute to a continuous agricultural residue supply.

6. Conclusions

In this article, we demonstrated how actors' willingness, actors' coordination and supply reliability influence the stability of agricultural residue supply to a large-scale processor. To this framework, we added actors' participation as a fourth influencing factor. Finally, we demonstrated the dynamic characteristic of these four aspects. This dynamic character is driven by the fifth factor, namely economic context. Furthermore, we revealed a complex interplay between these five factors and how they contribute to the goal of ensuring a continuous supply of biomass.

These results were deducted from an ABM of a corn stover value chain in Flanders. Our simulations showed that under none of the considered governance structure scenarios sufficient stover is traded for a CSPP to be able to depend only on corn stover as a feedstock. This is due to a limited number of single-pass harvesters available on the market to harvest the corn stover, limiting the number of farmers able to participate in the corn stover value chain. As such, our findings demonstrate the central role of custom harvesters in the corn stover value chain. Therefore, we advocate not to forget these crucial stakeholders in future analyses. Furthermore, the ABM simulation results showed that in case of a direct sale or request-for-purchase scenario, the market shows a rather unstable supply for corn stover. Conversely, cooperative scenarios show a more stable supply. As the supply in the bioprocessing cooperative scenario was significantly higher than in the supply cooperative scenario, this coordination scenario appears to be the most beneficial for the corn stover value chain.

Finally, the mixed-method approach was found to be useful to analyse the development of a complex system, such as the agricultural residue value chain. Although many assumptions are needed at various levels of the system, the results provide useful insights in the different factors that contribute to the goal of ensuring a continuous feedstock supply. Understanding these factors and their complex interplay is crucial to guide the successful future development of agricultural residue value chains.

For further research, we invite other researchers to test our framework to other case studies, and/or using other survey techniques, including panel survey data, in order to confirm and/or complement our findings.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2017.12.024.

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